Defense Technical Information Center Compilation Part Notice

ADP012895

TITLE: High-Frequency Hopping Conductivity of Two-Dimensional Electronic System in GaAs/A1GaAs Heterostructures [Acoustical Method]

DISTRIBUTION: Approved for public release, distribution unlimited
Availability: Hard copy only.

This paper is part of the following report:

TITLE: Nanostructures: Physics and Technology. 7th International Symposium. St. Petersburg, Russia, June 14-18, 1999 Proceedings

To order the complete compilation report, use: ADA407055

The component part is provided here to allow users access to individually authored sections of proceedings, annals, symposia, etc. However, the component should be considered within the context of the overall compilation report and not as a stand-alone technical report.

The following component part numbers comprise the compilation report:
ADP012853 thru ADP013001

7th Int. Symp. "Nanostructures: Physics and Technology"
St Petersburg, Russia, June 14–18, 1999

High-frequency hopping conductivity of two-dimensional electronic system in GaAs/AlGaAs heterostructures (acoustical method)

I. L. Drichko, A. M. Diakonov, V. D. Kagan, V. V. Preobrazenskiy†,
D. A. Pristinski, *I. Yu. Smirnov* and A. I. Toropov†
Ioffe Physico-Technical Institute, St Petersburg, Russia
† Semiconductors Physics Institute of SD RAS, 630090, Novosibirsk, Russia

Introduction

In the Quantum Hall regime when the Fermi level is situated between two adjacent Landau bands, the electrons are localized. This fact is confirmed by numerous direct current (DC) measurements of the resistivity of the high-mobility 2-dimensional systems in a magnetic field at low temperatures (see, for example, [1]). In this case DC conductivity seems to be of a hopping nature. However, the origin of the localized states is very difficult to determine in this experiments. The study of high-frequency conductivity $\sigma_{xx}^{\mathrm{hf}}$ proved to be useful in solving of this problem.

If the electrons are "free" the high-frequency conductivity $\sigma_{xx}^{\mathrm{hf}}$ should be the same as $\sigma_{xx}^{\mathrm{dc}}$, measured in DC experiment, and the difference between $\sigma_{xx}^{\mathrm{hf}}$ and $\sigma_{xx}^{\mathrm{dc}}$, from the other hand, points to the carrier localization. The high-frequency conductivity can be obtained from the propagation measurements of a surface acoustic wave (SAW). When a SAW propagates along the surface of a piezoelectric on which a semiconducting heterostructure with 2-dimensional electrons is superimposed, the elestic wave is accompanied with an alternating electric field. This field penetrates into the 2-dimensional conductivity canal, thus producing currents, Joule losses, and the SAW attenuation. Sound velocity changes also.

All these effects are governed by the high-frequency conductivity of a 2-dimensional system, and consequently if one observes Shubnikov–de Haas oscillations of the 2-dimensional system DC resistance in a magnetic field, similar oscillations should manifest themself in the SAW attenuation coefficient Γ and relative velocity change $\Delta V/V$.

In present work Γ and $\Delta V/V$ have been measured in a magnetic field up to 7 T on the GaAs/AlGaAs heterostructures with sheet densities $n = (1.3-7)\cdot 10^{11}\ \mathrm{cm}^{-2}$ and mobilities $\mu = (1-2)\cdot 10^5\ \mathrm{cm}^2/\mathrm{V}\cdot\mathrm{s}$.

Experimental results and discussion

The high-frequency conductivity is generally a complex value: $\sigma_{xx}^{\mathrm{hf}} = \sigma_1 - i\sigma_2$. For Γ and $\Delta V/V$ in this case we have:

$$\Gamma = 8.68\frac{K^2}{2}kA\frac{\dfrac{4\pi\sigma_1}{\varepsilon_s V}t(k)}{\left[1+\dfrac{4\pi\sigma_2}{\varepsilon_s V}t(k)\right]^2+\left[\dfrac{4\pi\sigma_1}{\varepsilon_s V}t(k)\right]^2}, \tag{1}$$

$$A = 8b(k)(\varepsilon_1+\varepsilon_0)\varepsilon_0^2\varepsilon_s\exp[-2k(a+d)],$$

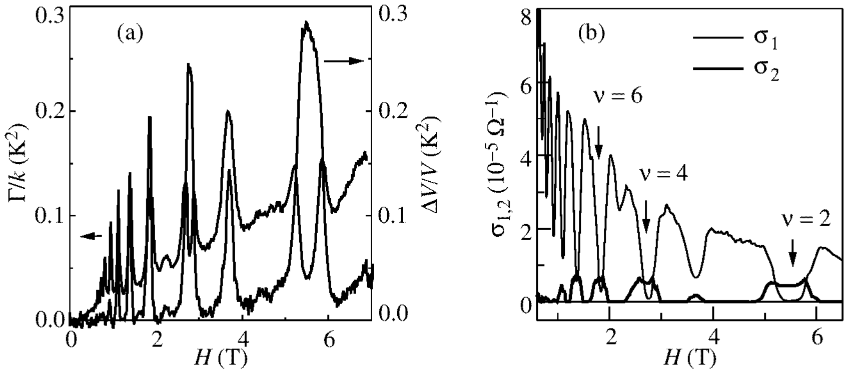

Fig. 1. (a) The experimental dependencies of Γ and $\Delta V/V$ on magnetic field H at $T = 1.5$ K, ($f = 30$ MHz). (b) The dependencies of σ_1 and σ_2 on H at $T = 1.5$ K, ($f = 30$ MHz).

$$\frac{\Delta V}{V} = \frac{K^2}{2} A \frac{\frac{4\pi\sigma_2}{\varepsilon_s V} t(k) + 1}{\left[1 + \frac{4\pi\sigma_2}{\varepsilon_s V} t(k)\right]^2 + \left[\frac{4\pi\sigma_1}{\varepsilon_s V} t(k)\right]^2},$$

where K^2 is the electromechanic coupling constant of $LiNbO_3$, k and V are wavevector and velocity of SAW, respectively, a is the gap between the piezoelectric and the heterostructure, d is the depth at which the 2-dimensional canal is burried, ε_1, ε_0, and ε_s are the dielectric constants of lithium niobate, vacuum and gallium arsenide respectively, b and t are some complex functions of a, k, ε_1, ε_0, ε_s.

In Fig. 1(a) the magnetic field dependencies of $\Gamma/(4.34AK^2k)$ and $(\Delta V/V)/(AK^2/2)$ for a sample with the carrier density $n = 2.7 \cdot 10^{11}$ cm^{-2} and mobility $\mu = 2 \cdot 10^5$ cm^2/V$\cdot$s are shown. One can see that these values oscillate with magnetic field, and for large filling factors the attenuation and velocity change peak do coinside, whereas for little filling factors the velocity change maxima coinside with the minima of the attenuation. Such a behaviour of these values could be explained sufficiently well by the (1).

The Eq. (1) provide us with σ_1 and σ_2 from the experimentally measured Γ and $\Delta V/V$. In Fig. 1(b) the dependencies of σ_1 and σ_2 on a magnetic field at $T = 1.5$ K are shown. As one can see, $\sigma_2 = 0$ in the magnetic field region where the Fermi level lies within the Landau band (semi-integer filling factors). From the experiment the results of which are shown in Fig. 2(b) it follows that the electrons are delocalized in this magnetic field region, and the conductivity is determined by its real part Re $\sigma_{xx}^{\mathrm{hf}} = \sigma_1$, which is of the same value as the DC conductivity $\sigma_{xx}^{\mathrm{dc}}$.

With the further increase of the magnetic field the Fermi level leaves the Landau band, a metal-dielectric transition takes place, and the electrons become localized in the random fluctuation potential of the charged impurities. In the vicinity of the transition, in the dielectric side of it, a discrepancy between the conductivity values is observed, so that $\sigma_1 > \sigma_{xx}^{\mathrm{dc}}$. In this case Γ still could be considered by the $\sigma_{xx}^{\mathrm{dc}}$ at the percolation level, but into Eq. (1) a factor less than 1 should enter, whose physical meaning is: the part of the area occupied by the "lakes of electrons" [2].

In the magnetic fields corresponding to the small integer filling factors the Fermi level is in the middle position between the Landau bands. One can see in Fig. 2(b) that in this

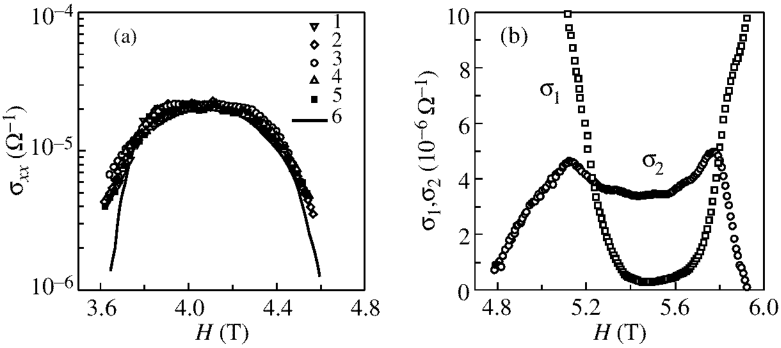

Fig. 2. (a) $\sigma_{xx}^{\rm dc}$ (solid line) and σ_1 versus H near the region of delocalized states. The symbols correspond to frequences f (MHz) and vacuum gap widths a (in μm): 1—213 and 0.3, 2—30 and 0.5, 3—150 and 0.3, 4—30 and 0.4, 5—90 and 1.2, $T = 4.2$ K. The sample has $n = 7 \cdot 10^{11}$ cm^{-2}. (b) The $\sigma_1(H)$ and $\sigma_2(H)$ at $T = 1.5$ K near the filling factor $\nu = 2$ for the sample with $n = 2.7 \cdot 10^{11}$ cm^{-2}, $f = 30$ MHz.

case σ_2 is far from being equal to zero, but to the contrary, is nearly an order higher than σ_1. According to Efros [3] such a relation between conductivities: $\sigma_1/\sigma_2 \sim 0.1$ ($f = 30$ MHz) can exist in the case of high frequency hopping conductivity, when the electrons are localized on the separate impurity atoms, that is so-called "two-site absorption". High-frequency hopping conduction occurs by electronic transitions between localized states with close energies. The states that are optimal for such transitions form compact pairs lying at a considerable distance from each other. There are no transitions between pairs, so that the pairs cannot give rise to transport of current in a static field, although a high-frequency field effects transitions within pairs, thereby producing polarization. Transitions within pairs can occur both with and without the help of phonons. In the former case, called the relaxation case, the energy E required for the transition of an electron within a pair is on the order of kT. At frequencies $\omega < \omega_{\rm ph}$ and $\hbar\omega < kT$, where $\omega = 2\pi f$ is the SAW frequency, $w_{\rm ph}$ is the characteristic phonon frequency order of 10^{12}–10^{13} s^{-1}, relaxation absorption dominates, and we shall be discussing precisely this case. For this mechanism the following relation holds:

$$\begin{aligned}
\mathrm{Re}\,\sigma_{xx}^{\rm hf} &= \sigma_1 = \frac{\pi^2}{8}\frac{\xi\omega e^4}{\varepsilon_s} r_\omega^2 g_0^2, \\
\mathrm{Im}\,\sigma_{xx}^{\rm hf} &= \sigma_2 = \frac{\pi}{2}\omega\frac{e^4}{\varepsilon_s} g_0^2 \left[\frac{r_\omega^3}{3} + r_T^3\right].
\end{aligned} \tag{2}$$

$$\begin{aligned}
r_w &= \frac{\xi}{2}\ln\left(\frac{\omega_{\rm ph}}{\omega}\right) \\
r_T &= \xi\ln\frac{J_0}{T};\; J_0 \simeq \varepsilon_B.
\end{aligned}$$

Where ξ is the localization length, r_w is the distance between localized states within one pair, e is the electron charge, $g_0 = dn/dE_{\rm F}$ is the density of states, $\varepsilon_{\rm B}$ is the Bohr energy. As one can see from (2), σ_1 does not depend on a temperature. In our experiment at high magnetic fields (small filling factors) σ_1 is independent of a temperature in the 1.5–3 K interval. This fact is also in favour of the hopping nature of the high-frequency conductivity.

With the aid of (2) one can estimate the localization length ξ. If for g_0 one takes $g_0 = m^*/\pi\hbar^2 = 1.8 \cdot 10^{25}\,\mathrm{cm}^{-2}/\mathrm{erg}$, from (2) it follows that $\xi = (3.0 \pm 0.3) \cdot 10^{-6}$ cm (5.5 T) and $\xi = (3.6 \pm 0.4) \cdot 10^{-6}$ cm (2.7 T). It should be noticed that for the same magnetic field these values differ only slightly from the magnetic length $\ell_B = \sqrt{\hbar c/eH}$ ($1.1 \cdot 10^{-6}$ cm (5.5 T), $1.56 \cdot 10^{-6}$ cm (2.7 T)) and the cyclotron radius $R_c = 2\nu/k_F$ in this sample ($2.4 \cdot 10^{-6}$ cm (5.5 T) and $4.7 \cdot 10^{-6}$ cm (2.7 T).

The $\sigma_1(T, H)$ and $\sigma_2(T, H)$ dependencies could be qualitatively explained by the change with T and H of the pair number actual for hopping. As T and H changes the number of localized electrons at the Fermi level varies due to the thermal activation to the upper Landau level.

Acknowledgements

The work is supported by RFFI No 98-02-18280 and MNTRF No 97-1043 grants.

References

[1] M. Furlan, *Preprint Cond-mat* 9712304 (1997).

[2] I. L. Drichko, A. M. D'yakonov, A. M. Kreshchuk, T. A. Polyanskaya, I. G. Savel'ev, I. Yu. Smirnov and A. V. Suslov, *Fiz. Tekh. Poluprovodn.* **31**, 451 (1997).

[3] A. L. Efros, *Zh. Eksp. Teor. Fiz.* **89**, 1057 (1985).